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SUMMARY PAGE

THE PROBLEM

To determine whether, and to what extent, supplementing visual waterfall displays with redundant auditory signals (i.e., bimodal displays) enhances detection of sonar targets. This study was designed to rule out several potential artifacts which complicate the interpretation of previous research on bimodal sonar displays. This study also investigated the extent to which signal uncertainty and the degree of spatial compatibility between visual and auditory signals in bimodal displays affects target detection performance.

THE FINDINGS

The signal-to-noise ratio (SNR) at which targets were just barely detectable was 1.1 dB lower for bimodal displays than for single-modality displays. This result is in close agreement with most previous studies of bimodal sonar displays. The results also show that the deterioration in detection performance with increased signal uncertainty is considerably less for auditory displays than for visual displays. In this study, increased spatial compatibility between visual and auditory signals did not facilitate detection on bimodal displays. More effective methods making auditory and visual signals spatially compatible are recommended for further research.

APPLICATION

The findings confirm that bimodal displays enhance target detection performance on sonar waterfall displays, and suggest that auditory displays offer advantages for operational conditions with high signal uncertainty.

ADMINISTRATIVE INFORMATION

This investigation was conducted under Naval Medical Research and Development Command Research Work Unit 65856N - M0100.001-5001. It was submitted for review on 5 January 1989, approved for publication on 22 March 1989, and has been designated as Naval Submarine Medical Research Laboratory Report No. 1132.

ABSTRACT

An experiment was conducted to determine whether bimodal (auditory plus visual) displays enhance operators' basic ability (perceptual sensitivity) to detect sonar targets. The possibility that operators' decisions about how to respond when uncertain (response criteria) contributed to the findings was ruled out by using data collection and analysis procedures based on the Theory of Signal Detectability. Also the detectability of the visual and auditory signals used in the bimodal display condition were carefully equated. This ruled out the possibility of a false bimodal effect due to operator's responding on the basis of the more detectable of the two signals on the bimodal display. This study also examined the effects of signal uncertainty and the degree of spatial correlation (compatibility) between the visual and auditory signals on the bimodal display. It was expected that spatially correlated auditory signals would facilitate detection in the bimodal condition by cluing the operator where to look on the visual display.

Increased signal uncertainty produced an increase in the average signal-to-noise ratio (SNR) at which the signal could first be detected. The increase in the SNR needed for detection was significantly greater for the visual display (3.0 dB) than for the auditory display (1.2 dB). On the bimodal displays, signals were detected at significantly lower SNRs than on single-modality displays (average 1.1 dB difference). Increased compatibility between the visual and auditory signals did not increase the advantage of bimodal displays; nor did the advantage of bimodal displays change with signal uncertainty.

The findings show that bimodal displays improve signal detection performance in sonar systems. They rule out the possibility that the advantage of bimodal displays is attributable to changes in operators' response criteria and/or artifacts caused by differences in the detectability of the visual and auditory signals. They also suggest that auditory displays offer advantages for real-world sonar operations, where signal uncertainty is often high. The method used to make auditory and visual signals spatially compatible in this study was not successful. More effective methods for creating spatial compatibility are recommended for future research.

EFFECTS OF BIMODAL DISPLAYS ON SONAR TARGET DETECTION

The earliest sonar systems relied exclusively on the auditory modality to present information to the operator. Over the past decade or two there has been a shift toward use of visual displays in sonar, although auditory displays are still regarded as an important component in submarine sonars. These changes from auditory to bimodal and visual displays have been made in the absence of satisfactory data on the effects of the various display types on operator performance. Previous research on bimodal information presentation has tended to fall into one of two categories: basic research whose applicability to sonar operations is uncertain, or applied research plagued by methodological problems.

A number of studies in the first category have reported that detection performance is improved when the same information is presented both visually and aurally (Brown and Hopkins, 1967; Buckner and Mc Grath, 1963; Fidell, 1970; Loveless, Brebner, and Hamilton, 1970). However, the tasks and stimuli employed in these studies differed in important respects from those used in sonar systems.

One of the earliest applied studies employed a vigilance task (Colquhoun, 1975). His subjects monitored visual, auditory, and bimodal displays for long periods of time for a small, infrequent change in the signal. The signal consisted of an increase in the intensity of one of four pure tones mixed with broadband noise in the auditory modality, and/or an increase in brightness of one of four rings on a visual display. The percentage of signals detected was much greater for the auditory display than for the visual display, and the bimodal display produced a small additional improvement over the auditory display. However, the false alarm rate was also greater for the bimodal display than for the auditory display. Therefore, the slight superiority of the bimodal display may have been due to a relaxation of the response criterion, rather than an increase in perceptual sensitivity.

The problem of interpretation due to possible shifts in the response criterion is also present in subsequent applied studies. Kobus, Russotti, Schlichting, Haskell, Carpenter, and Wojtowicz (1986) presented simulations of sonar target emissions generated by the U. S. Navy Sonar Operational Trainer in a background of sea noise. The target was presented at any one of 10 sectors which the subject could search sequentially. The target intensity was increased until the subject reported its presence in the correct sector. Visual signals were presented on a waterfall-type display (which displays frequency horizontally and time vertically). For some signals, the visual display produced best detection; for others, auditory presentation was best. The signal

level at which detection occurred in the bimodal condition was not significantly different from that for the better single modality.

Other applied studies using the same type of visual display have reported significant advantages of bimodal presentation (Luria and Jacobsen, 1986; Lewandowski and Kobus, in press). In both studies, bimodal presentation produced a reduction of about 1.0 dB in the signal level required for detection. The possibility cannot be ruled out that discrepancy between these studies and Kobus et al. (1986) in the bimodal effect is due to shifts in the response criterion. It would be of interest to conduct further research using realistic sonar displays and tasks, to determine if changes in response criterion between display conditions can account for these results.

Another potential problem arises if the signals are not carefully equated for detectability in the auditory and visual modalities. In the bimodal condition, the subject may respond on the basis of the more detectable of the two signals. If the signal were sometimes more detectable in the visual modality, and sometimes in the auditory, then, <u>on the average</u>, the signal level required for detection in the bimodal condition would be spuriously less than those in either the visual or auditory conditions. That is, there would be an apparent advantage of bimodal presentation, even though the subjects were responding on the basis of one modality in the bimodal condition.

The primary purpose of the present research was to determine whether bimodal displays enhance an operator's perceptual sensitivity in detecting sonar targets, relative to single-modality displays. The method of the present study differed from that of previous applied work in two important respects. First, the possibility that changes in subjects' response criteria contributed to the observed differences among experimental conditions was ruled out by using data collection and analysis procedures based on the Theory of Signal Detectability (TSD) (Green and Swets, 1966). Second, the possibility of obtaining a spurious bimodal effect was minimized by carefully equating the detectability of the visual and auditory signals used in the bimodal condition.

This study also examined the effects of signal uncertainty and increased spatial compatibility between visual and auditory information in bimodal displays. In the high compatibility condition, the auditory stimulus (noise and signal, if any) was lateralized. This caused stimuli with predominantly low frequencies to be heard toward the left side of the head, while those with predominantly highs were heard toward the right. The position in which the auditory signal was heard corresponded roughly to its position on the visual display, which presented the stimulus spectrum horizontally.

Signal uncertainty and display compatibility were of interest because they represent variations in the detection task and alternatives for bimodal display design that occur, or could be used, in real sonar operations. The fact that signal uncertainty produces a decrement in detection performance is well documented (Sperling and Dosher, 1986; Swets, 1984). In contrast, it is at present unknown whether increased compatibility between display modalities enhances bimodal detection performance. With the high compatibility, bimodal display, the auditory signal may cue the operator where to look on the visual display. It was therefore anticipated that greater spatial compatibility between auditory and visual displays would be associated with a larger bimodal advantage. It was also of some practical interest to determine whether display compatibility and signal uncertainty interact, i.e., whether increased display compatibility reduces the performance decrement due to increased signal uncertainty.

METHOD

Overview: Effects of three major variables on detection performance were investigated in a simulated sonar task. Signals were noise bands, nominally 200 Hz wide, with center frequencies (CFs) of 0.9, 1.8, 3.6, and 7.2 kHz. The signal was presented in a background of white noise.

Subjects viewed a modified waterfall-type display and/or heard the same signals presented aurally. Independent variables included (1) display modality (visual, aural, or bimodal), (2) signal uncertainty (0 or 2 bits), and (3) lateralized (dichotic) or diotic presentation of the auditory signal.

The auditory stimulus (signal plus masker) was lateralized in one condition by low-passing the left ear input and high-passing the right ear input. This caused the low frequency signal to be heard on the left side of the head, moderate frequency signals in the middle, and the highest frequency signal on the right. The visual display also presented the stimulus spectrum horizontally, with lowest frequencies on the left. Therefore, when the display was bimodal and the auditory stimulus was lateralized, the positions of the signal on the visual and auditory displays were correlated. This was called the "high compatibility" condition. When the auditory signal was not lateralized, there was no spatial correlation between the visual and auditory signals; this was called the "low compatibility" condition.

Signal uncertainty was manipulated by presenting either a single signal repeatedly on a given block of test trials (0 bits uncertainty), or by presenting one of four signals (2 bits) in a random sequence.

Each test trial involved a two-alternative forced choice. Signal level was adaptively varied within each block of test trials to maintain a fixed probability of correct response. The signal-to-noise ratio (SNR) required for detection was estimated by averaging the maximum and minimum signal levels in the latter portion of each test block.

Stimuli: Signals were 0 to 100 Hz bands of noise multiplied by sinusoids with frequencies of 0.9, 1.8, 3.6, or 7.2 kHz. The 3 dB bandwidth of each signal was 209 Hz, and the rolloff was 115 dB per octave on both sides. The signals were amplitude modulated by a 15 Hz sine wave with an RMS amplitude of 1.5 V ac and a 5 V dc offset. The signals had 20 ms rise and fall times which followed a cosine-squared function. The spectrum level of the noise masker was constant at 25 dB (re: .0002 dynes/cm^2) out to 14 kHz, after which it gradually rolled off. The headphones were Sennheiser model 430.

The same input was fed to both the visual and the auditory displays, except that the auditory input was further filtered in the lateralized condition. Lateralization was accomplished by passing the left channel through an equalizer in series with a low-pass filter, and the right channel through an equalizer in series with a high-pass filter. The transfer functions for each channel, as plotted directly from a 1024-point digital spectrum analyzer, are shown in Figure 1. The solid horizontal line shows the level of the diotic input. Note that the high-pass (right ear) channel was boosted about 12 dB at 7.2 kHz relative to the diotic input. Similarly, the low-pass (left ear) channel was boosted 12 dB at 900 Hz. The equalizer and filter settings were developed in pilot testing with four listeners who had bilaterally normal hearing. The filter characteristics and signal CFs were chosen so that the perceived positions of the signals were maximally separated and reliably judged.

Visual signals were presented on a Spectral Dynamics waterfall-type display, which was part of a sonar system. The input was fed directly to the system display board, bypassing filters. Only the portion of the input from 0 to 10 kHz was presented on the visual display. The horizontal width of the signal plus noise on the display was 25 cm, which included 400 pixels. The average luminance of the noise signal alone was 0.026 cd/m^2, and the average luminance measured in the center of the signals at an SNR of 0 dB was 0.078 cd/m^2. The total vertical height of the 10 raster lines used was 1.2 cm. The viewing distance was 85 cm.

Each raster line on the visual display represented the stimulus energy integrated over a period of 0.1 s. The most recent power spectrum was displayed on the top raster line, and the earlier spectra were each moved down one line each 0.1 s. Black paper was used to cover the lower part of display, allowing

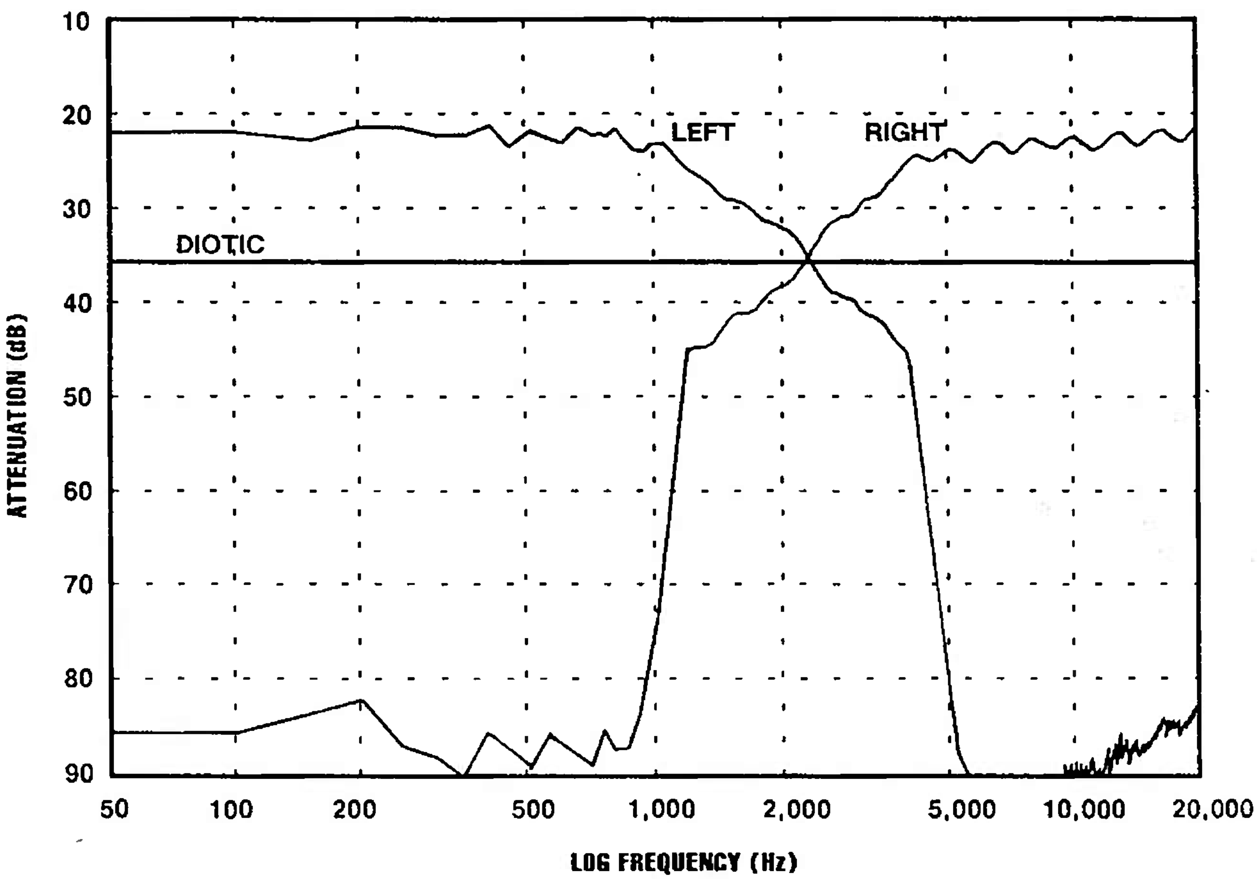

Figure 1. Amplitude responses of filters used to lateralize the auditory stimulus in the dichotic (high compatibility) condition.

only 10 raster lines (1.0 s of signal) to be viewed.

Procedure: Subjects were tested individually in a partially darkened, double-walled audiometric booth. Each subject participated in three training sessions and ten test sessions of approximately 90 minutes duration each.

An adaptive tracking procedure was used to estimate the signal level required for detection in each condition. Each estimate was based on a block of 80 test trials. During the test block, the signal level was decreased a predetermined step size after every three consecutive correct responses, and increased the same step size after each error. This constrained the percentage of correct responses to be 79.4 (or equivalently, $d'=1.16$). The signal level in each test block was initially set 10 dB higher than an initial level based on previous testing. The step size was 6 dB until the first error, and 2 dB for the remainder of the block.

On each test trial, the subject judged whether the signal had appeared in the first or second of two observation intervals by pressing one of two 4-inch square boxes arranged horizontally on touch screen, positioned within easy reach of the right index finger. The observation intervals were 1.0 s long, and were separated by a 0.5 s pause. The system waited 4.0 s for the subject's response, after which a prompting message appeared on the touch screen and the touch screen monitor beeped. The system then waited up to 4.0 additional seconds for a response before delivering feedback. If the response was correct, a "+" sign was displayed and one short beep was sounded; feedback for errors and non-responses was a "-" sign and two beeps. The next test trial began one second after the feedback.

Over the three training sessions, each subject completed 25 blocks of practice trials, representing each of the 25 stimulus conditions. The conditions were run in a fixed order in training. In each test session, each subject completed nine test blocks, including three in the auditory modality only, three visual only, and three bimodal. The auditory and visual conditions were alternated over the first six blocks, with an auditory or visual block randomly selected to be the starting condition. The same signal or signals were used throughout a given session. Each of the four signals was used once in sessions 1 through 4, the order being random. In session 5, all four signals were used (high uncertainty condition). In the first five sessions, the auditory display was lateralized for three of the subjects (determined randomly) and diotic for the others. Sessions 6 through 10 replicated the first five sessions, except that the auditory display was switched to the type, lateralized or diotic, that the subject had not experienced in sessions 1 through 5.

Running the single-modality test blocks prior to the bimodal

blocks in each session made it possible to equate the auditory and visual signals for equal detectability in the subsequent bimodal test blocks. The initial level of the auditory signal in the bimodal blocks was set at the average measured "threshold" from the three auditory test blocks run earlier in the same session. The initial level for the visual signal was set in the same manner. The signal levels were set individually for each subject, based on his or her prior data.

In the high uncertainty sessions (numbers 5 and 10), the signal levels for the single-modality test blocks were set at the average measured threshold from the low uncertainty, single-modality test blocks run in the four preceding sessions. The initial signal levels for the low uncertainty, single modality blocks in sessions 1 to 4 and 6 to 9 were set at each individual subject's measured threshold in training for the same condition. Initial thresholds in training blocks were set to the same level for all subjects, based on pilot data.

At the start of each test block, the subject was told the display modality, the number of alternative signals which could appear, and whether the auditory signal would be lateralized. Care was also taken to ensure that the subject had the earphones oriented properly.

<u>Subjects</u>: The subjects were two women and three men between the ages of 22 and 32 years. Subjects were audiometrically normal and had normal vision. Hearing was tested to ANSI S3.21-1978 specifications, and vision was low normal or better on the Vistech, Inc. VCTS 6000 contrast sensitivity test.

<u>Data Reduction</u>: The raw data for each block of test trials consisted of a trial-by-trial record of attenuation relative to the initial level at the beginning of the block. The record showed a local maximum or peak whenever the subject made an error after a series of three consecutive correct responses, which caused the signal attenuation to be decreased on the next trial. It showed a local minimum or valley whenever three consecutive correct responses were made after one or more errors, which caused the attenuation to be increased for the next trail.

For each block, the average deviation from the initial attenuation was computed by taking the mean of an equal number of peaks and valleys after the first peak that occurred after a valley. If the number of peaks and valleys after the first valley and peak were not equal, one peak or valley closest in time to the beginning of the block was dropped. The deviation was added to the initial attenuation and converted to the signal to noise ratio (SNR). In addition, the data from each block were fit with a psychometric function of the form:

$$d' = m\ (E/N_0)^k$$

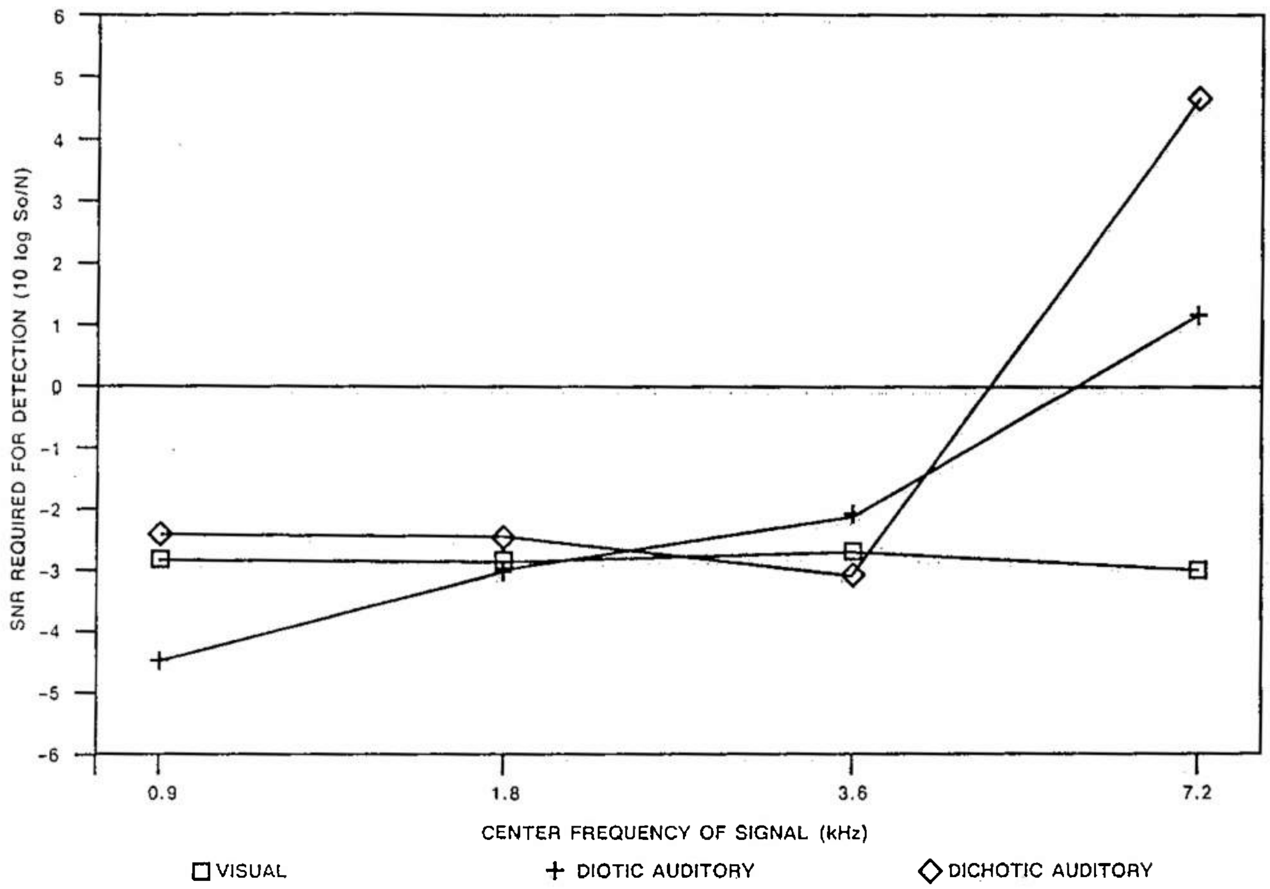

Figure 2. SNR required for detection with single-modality displays, by signal type and center frequency (low signal uncertainty condition).

RESULTS

Effects of Signal Center Frequency and Signal Type in Single-Modality Displays: Figure 2 shows the SNR required for detection as a function of the CF of the signal and type of signal (visual, diotic auditory, and dichotic auditory). These data are for the low uncertainty condition only. Up to and including the 3.6 CF kHz signal, the visual and auditory SNRs required for detection were roughly comparable. However, for the 7.2 kHz signal, auditory SNRs were dramatically higher. Analysis of variance (ANOVA) showed that the effects of CF and the interaction of CF X Signal Type were both significant at the p=.001 level ($F(3,12)$=11.3 and $F(6,24)$=11.7, respectively). The main effect of Signal Type was significant at the p=.05 level ($F(2,8)$=5.8).

In addition to the difference between visual and auditory signals noted above, it appears from Figure 2 that there is a difference in SNR for 7.2 kHz CF signal for diotic as opposed to dichotic auditory signal. This difference was not significant by Tukey's Honestly Significant Difference test ($q(12,48)$=1.8, p>.05).

Effects of Signal Uncertainty and Signal Type in Single-Modality Displays: Figure 3 shows the data for single-modality displays averaged over CFs. The SNR required to detect the signal increased significantly with signal uncertainty ($F(1,4)$=15.8, p< .025). Signal uncertainty had a much greater effect on visual signals than on auditory signals ($F(2,8)$=24.7, p< .001). In the low uncertainty condition, SNR for visual signals averaged 0.8 dB lower than that for auditory signals presented diotically. In the higher uncertainty condition however, SNR for visual signals averaged 1.3 dB greater than that for auditory signals presented diotically. Mean SNRs for auditory signals presented dichotically tended to be greater than those for both visual and diotic auditory signals at both levels of uncertainty. However, the overall main effect of Signal Type in Figure 3 was not significant ($F(2,8)$=3.2, p> .05).

Effects of Bimodal versus Single-Modality Presentation: Table 1 shows the effect of bimodal as opposed to single-modality presentation. The values in this table are the differences in SNRs between bimodal and single-modality displays for each of the conditions shown. A 2 X 2 ANOVA was performed to examine differences among the four means at the bottom of the table (i.e., collapsing over signal CF).

There was a highly significant overall advantage of bimodal as opposed to single-modality displays. For bimodal displays the SNR required to detect the signal averaged 1.1 dB less than the SNR for single-modality displays ($F(1,19)$=42.4, p< .001).

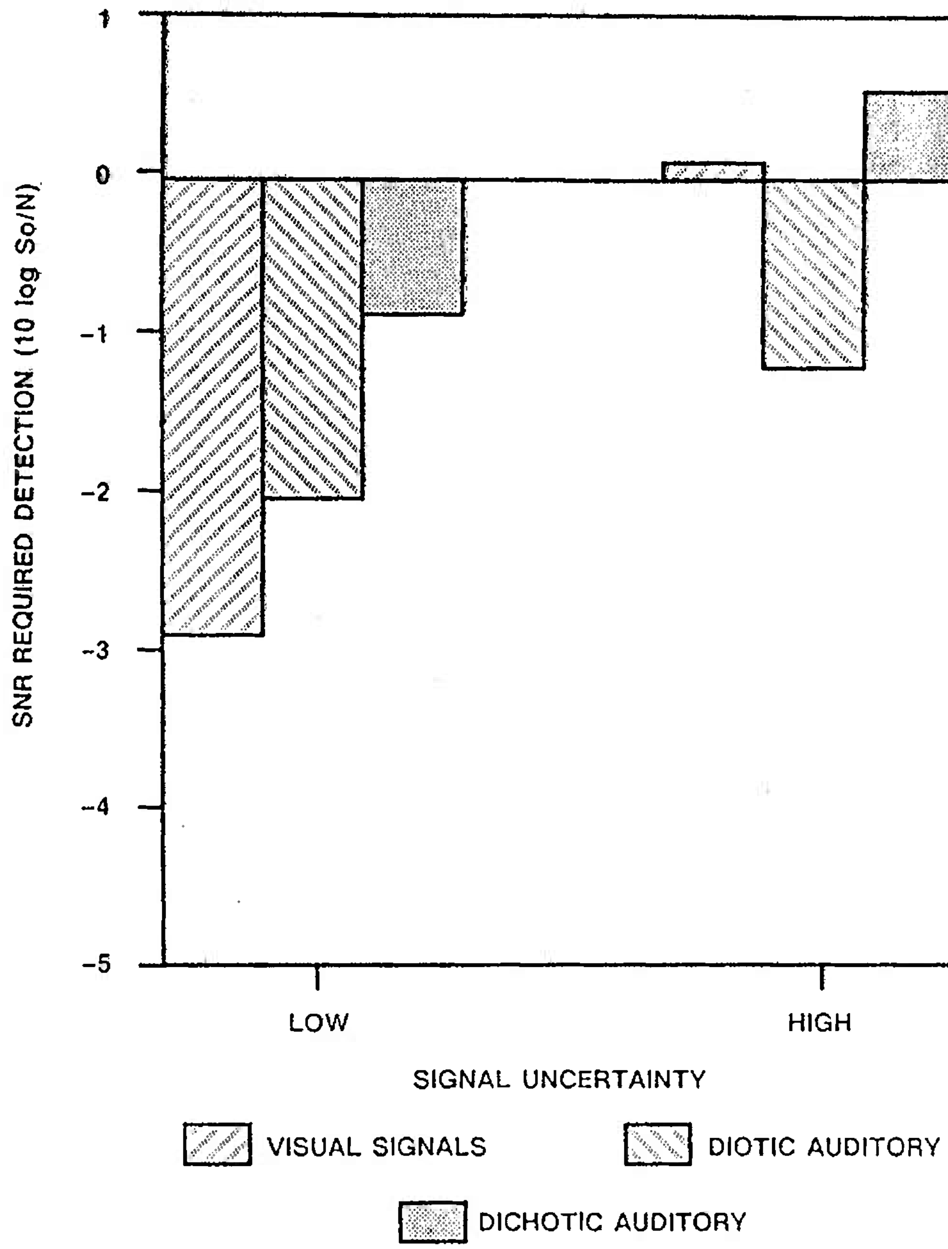

Figure 3. SNR required for detection with single-modality displays as a function of signal type and uncertainty.

Table 1. Bimodal facilitation as a function of center frequency of signal, type of authority display, and signal uncertainty.

Signal uncer-tainty	Center frequency of signal (kHz)	Type of auditory display: Diotic (Low compatibility)	Type of auditory display: Lateralized (High compatibility)
Low	0.9	-1.1	-1.8
	1.8	-1.0	-1.3
	3.6	-0.5	-0.9
	7.2	-0.8	-0.9
Means for low uncer-tainty condition		-0.8	-1.2
High	-----	-1.5	-0.9

Note: Entries are 10 log S/N for bimodal displays minus the same value for the corresponding unimodal displays. Negative numbers indicate greater sensitivity.

Contrary to expectations, the bimodal facilitation did not increase significantly with signal uncertainty ($\underline{F}(1,4)=0.8$, $\underline{p} > .05$). Increased display Compatibility (diotic versus dichotic auditory signal) also failed to produce greater bimodal facilitation ($\underline{F}(1,4)=0.2$, $\underline{p} > .05$). The interaction of Compatibility X Uncertainty was also not significant ($\underline{F}(1,4)=3.6$, $\underline{p} > .05$).

An additional ANOVA was performed to determine whether the advantage of bimodal presentation changed with signal CF in the low signal Uncertainty condition. These data are shown in the upper four rows of Table 1. The effect of signal CF was not significant ($\underline{F}(3,12)=1.1$, $\underline{p} > .05$). The effect of Compatibility (diotic versus dichotic auditory stimulus) was also not significant ($\underline{F}(1,4)=3.0$, $\underline{p} > .05$). Nor was the interaction of CF X Compatibility significant in these data $\underline{F}(3,12)=0.2$, $\underline{p} > .05$).

Practice Effects within Sessions: In each test session, test blocks in the visual and auditory display conditions were run prior to the bimodal condition so that results of the former could be used to equate the detectability of visual and auditory signals in the latter. Even though the subjects were well practiced before the test sessions began, it was possible that practice effects within test sessions might emphasize any difference in SNR between bimodal and single-modality test blocks. That is, any within-session practice effect could lead to

overestimation of the bimodal effect.

The within-session practice effect was therefore evaluated. Since each stimulus condition was tested three times in each session, it was possible to examine trends over repeated test blocks of the same stimulus conditions. The mean SNRs required for detection were computed for first, second, and third repetitions of test conditions, averaged over all subjects and test conditions. The mean SNRs were -2.1, -2.2, and -2.0 dB for first, second, and third repetitions, respectively. For four of the five subjects, the mean SNR required for detection increased from the first to the third repetition. These results show that there was no practice effect; that is, the change in SNR was small and in the wrong direction.

Table 2 shows the average values of k when the data were fit with the function:

$$d' = m\ (E/N_0)^k.$$

The average value of k across conditions is 1.54, with generally little variation among conditions. In particular, the similarity of the k values for the auditory and visual conditions means that when performance was equated at one level, it was also equated as signal level varied in the bimodal condition.

Table 2. Average value of k from maximum likelihood fit to the psychometric function, d' = m

Signal uncertainty	Center frequency of signal (kHz)	Display Modality					Means
			Auditory		Bimodal		
		Type of Auditory Display					
		Visual	Lateral	Diotic	(HC)	(LC)	
Low	0.9	1.39	1.23	1.52	1.43	1.67	1.45
	1.8	1.27	1.72	1.75	1.68	1.52	1.59
	3.6	1.41	1.82	1.72	1.31	1.44	1.54
	7.2	1.61	1.86	1.58	1.45	2.17	1.73
	Means	1.42	1.66	1.64	1.47	1.70	1.58
High	---	1.64	1.13	1.67	1.65	1.39	1.50
Overall Means		1.53	1.40	1.66	1.56	1.55	1.54

High compatibility condition
Low compatibility condition

DISCUSSION

The results show a highly consistent advantage of bimodal over single-modality displays. The SNR required to detect the signal averaged 1.1 dB less with bimodal displays. This finding is in close agreement with the two previous applied studies which used detection rather than vigilance or search tasks (Luria and Jacobsen, 1986; Lewandowski and Kobus, in press). Both of these studies reported bimodal facilitations of about 1.0 dB. The fact that the effect was replicated in the present study, which used a TSD-based method and equated the signals for detectability, provides strong evidence that bimodal displays enhance operators' perceptual sensitivity; that is, the effect is not due to changes in response criterion, nor a statistical artifact.

The bimodal improvement is in good agreement with that predicted by optimal integration of the information in the two channels (Green and Swets, 1966, p. 238). Assuming that the information in the two channels is independent, the bimodal d' should be the square root of 2.0 times the unimodal d's. Since the overall psychometric function has an exponent of 1.54, a square root of 2.0 change in performance is comparable to a threshold decrease of 0.96 dB. Thus, the results are consistent with optimal integration of the information in the two modalities.

Both the present research and the Luria & Jacobsen and Lewandowski & Kobus studies used sonar-type displays and stimuli. But bimodal displays are potentially applicable to a wide variety of human-machine systems, including aircraft displays and air-traffic control. A useful direction for future research would be to investigate the generality of the bimodal effect with a wider range of displays, signals, and tasks.

In addition to confirming the benefit of bimodal presentation, the present results provide information on how task and display-design variables affect detection performance. As expected, increased signal uncertainty produced a decrement in detection performance. For single-modality displays, increasing uncertainty from 0 to 2 bits increased the SNR required to detect the signal by an average of 1.8 dB. The uncertainty decrement was significantly greater for visual than for auditory displays. Increased signal uncertainty increased the SNR for visual detection an average of 3.0 dB, but increased the SNR for auditory detection only 1.2 dB. For purposes of comparison, the uncertainty decrement was computed for an ideal processor monitoring one versus four independent channels, using the method described by Nolte and Jaarsma (1967) and Peterson, Birdsall, and Fox (1954). This result was also 1.2 dB, suggesting that the auditory display allowed subjects to monitor the four channels in parallel. These findings suggest that auditory displays may

offer practical advantages for real-world sonar operations, where signal uncertainty is often high.

The advantage of bimodal as opposed to single-modality displays did not increase with signal uncertainty. Of course, the fact that these variables had additive effects on the SNR required for detection does not imply that their effects would be additive in terms of the probability of a correct response, P(C). Since the relationship between SNR and P(C) is non-linear in general, variables whose effects are additive in terms of SNR may be non-additive if studied by a procedure that holds SNR constant and allows P(C) to vary.

Contrary to expectation, increased compatibility between the auditory and visual displays (going from diotic to dichotic auditory stimuli) did not produce greater bimodal facilitation. Dichotic auditory stimuli also produced poorer detection performance than did diotic stimuli in single-modality displays. Introspective reports from the subjects indicated that the dichotic (lateralized) auditory stimuli did not provide strong spatial cues. Although the lowest frequency signal (0.9 kHz CF) was clearly heard on the left side, the perceived locations of the higher frequency signals were somewhat variable and uncertain. It is concluded that lateralizing the auditory stimulus by varying the interaural amplitude alone is not a useful way to increase display compatibility, and thereby detection performance. This does not rule out the possibility that other means of enhancing compatibility would facilitate detection. In particular, it is recommended that future research use interaural phase differences and/or mimic the direction-dependent amplitude response of the human head and pinna.

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(U) Effects of bimodal displays on sonar target detection

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An experiment was conducted to determine whether bimodal (auditory plus visual) displays enhance operators' basic ability (perceptual sensitivity) to detect sonar targets. The possibility that operators' decisions about how to respond when uncertain (response criteria) contributed to the findings was ruled out by using data collection and analysis procedures based on the Theory of Signal Detectability. Also the detectability of the visual and auditory signals used in the bimodal display condition were carefully equated. This ruled out the possibility of a false bimodal effect due to operators' responding on the basis of the more detectable of the two signals on the bimodal display. This study also examined the effects of signal uncertainty and the degree of spatial correlation (compatibility) between the visual and auditory signals on the bimodal display. It was expected that spatially correlated auditory signals would facilitate detection in the bimodal condition by cluing the operator where to look on the visual display.

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Increased signal uncertainty produced an increase in the average signal-to-noise ratio (SNR) at which the signal could first be detected. The increase in the SNR needed for detection was significantly greater for the visual display (3.0 dB) than for the auditory display (1.2 dB). On the bimodal displays, signals were detected at significantly lower SNRs than on single-modality displays (average 1.1 dB difference). Increased compatibility between the visual and auditory signals did not increase the advantage of bimodal displays; nor did the advantage of bimodal displays change with signal uncertainty.

The findings show that bimodal displays improve signal detection performance in sonar systems. They rule out the possibility that the advantage of bimodal displays is attributable to changes in operators' response criteria and/or artifacts caused by differences in the detectability of the visual and auditory signals. They also suggest that auditory displays offer advantages for real-world sonar operations, where signal uncertainty is often high. The method used to make auditory and visual signals spatially compatible in this study was not successful. More effective methods for creating spatial compatibility are recommended for future research.